Geometric Design, Speed, and Safety

Richard J. Porter, Eric T. Donnell, and John M. Mason

A performance-based approach to the interaction of geometric design, speed, and safety is considered given the availability of two key documents: the *Highway Safety Manual* and *Modeling Operating Speed: Synthesis Report*. A historical look at the concept of design speed shows that although the definition of design speed has changed on more than one occasion, the same basic philosophy that related design speed to a safe speed is still reflected in current policy in supplemental guidance related to the selection of design speed. A conservative approach to establishing design criteria, used to address the range of driver, vehicle, and roadway conditions and capabilities that a designer must consider, is demonstrated. Operating speeds are shown to be higher than design speeds for design speeds of approximately 55 mph or less. This outcome may be considered undesirable, but that categorization seems to be based more on subjective judgments of what is desirable than on actual safety findings. Finally, the idea of speed management through the use of roadway geometrics (i.e., geometric designs that influence driver selection of operating speed)— one component of self-enforcing, self-explaining roadway design—is explored. Findings uncover possible challenges to implementing this idea. Five related questions are addressed: (*a*) What is known about the relationships between road geometry and operating speeds? (*b*) To what degree does road geometry influence operating speeds? (*c*) How are safety and security influenced by road geometry? (*d*) What are the potential impacts on large vehicles? and (*e*) What is the nature of the speed–safety trade-off?

Speed has a central role in engineering activities conducted throughout the life cycle of a road. It is a key consideration in the geometric design of highways and streets. Decisions and stakeholder consensus regarding design speed and anticipated operating speeds are usually looked at during preliminary engineering activities for a project and ultimately influence a number of subsequent project decisions. Challenges associated with the speed-related outcomes of the current design decision-making framework have been documented (*1–2*). Relationships between design speeds, operating speeds, and posted speeds have been empirically demonstrated and labeled undesirable for certain roadway types. Excessive speeds have been identified as an important contributory factor in a significant percentage of severe crashes (*3*). The vehicle speed–dependent design process has also been branded as a major detriment to the safety and security of nonmotorized users in urban and residential areas [e.g., see background discussion in Dumbaugh and Li (*4*)].

R. J. Porter, Department of Civil and Environmental Engineering, University of Utah, 110 Central Campus Drive, Room 2133, Salt Lake City, UT 84112. E. T. Donnell, Department of Civil and Environmental Engineering, Pennsylvania State University, Sackett Building, Room 223B, University Park, PA 16802. J. M. Mason, Department of Civil Engineering, Auburn University, 238 Harbert Engineering Center, Auburn, AL 36849. Corresponding author: R. J. Porter, richard.jon.porter@utah.edu.

Several ideas and solutions to these challenges have been offered. The research literature is populated with studies that link operating speed to geometrics in an attempt to understand and predict speed behavior. In recent years, terms and design practices (both international and domestic) have been introduced, including inferred design speed; self-enforcing, self-explaining design; context-sensitive design and solutions; complete streets; design consistency; speed management; traffic calming; and speed dampening; however, other than a few changes in definition, the role of speed in U.S. highway design practice has remained relatively the same. Quantitative analysis and results (e.g., demonstrated safety relationships) to support the distinction between desirable and undesirable speed-related outcomes do not exist. Most discussion of speed-related problems is based on how closely observed speed relationships conform to subjective judgments of what is ideal. Terms such as "speed harmony" and "speed discord" have been proposed in this context (*5*).

This paper takes an objective look at the interaction of geometric design, speed, and safety. A performance-based approach to this topic is evolving, given the availability of two key documents: the *Highway Safety Manual* (HSM) (*6*) and *Modeling Operating Speed: Synthesis Report* (*7*). Particular consideration is directed to the use of road geometry as a speed-management strategy. The term "self-enforcing, self-explaining roadway design" has more recently been attached to this concept.

The paper first takes a historical look at intended and actual relationships between design speed and operating speed. Other speed-dependent geometric design criteria are then discussed, with quantitative illustrations that demonstrate the margins of safety built into some design parameters. Observed speed outcomes are then described, with references to other work with thorough coverage of this topic. Finally, the idea of speed management through the use of road geometrics, one component of self-enforcing, self-explaining roadway design, is explored.

DESIGN SPEED AND OPERATING SPEED: A HISTORICAL LOOK

Relationships between design speed and operating speed have been explored on several occasions [e.g., see Fitzpatrick et al. (*1*), Donnell et al. (*5*), and Tarris et al. (*8*)]. This section provides a historical look at definitions, guidance, and assumed relationships between design speed and running speed in design policies dating back to 1940. Results of this review show that, while the definition of design speed has changed twice, its basic application and assumed implications have not. Relationships between design speed and operating speed as well as between design speed and safety that were assumed to exist more than 70 years ago still influence design guidance in current policies and practice.

Road design practice in the United States is based on selecting and applying a design speed. A design speed is usually selected during

the preliminary engineering activities of a project and influences subsequent design decisions. A review of AASHTO design policies revealed three different definitions of design speed:

- Before 1954: the maximum appropriately uniform speed that probably will be adopted by the faster group of drivers but not, necessarily, by the small percentage of reckless ones (*9*);
- 1954 to 2001: the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern (*10*); and
- 2001 to the present: a selected speed used to determine the various geometric design features of the roadway (*11*).

AASHTO recommends that selection of a design speed "should be a logical one with respect to the topography, anticipated operating speed, the adjacent land use, and the functional classification" of the highway or street (*11*). Fitzpatrick et al. provide a synthesis of current practices for selecting a design speed that were identified through a survey of state transportation agencies (*1*). The survey asked respondents to use their engineering judgment to document the relationship between design speeds, anticipated posted speed limits, and anticipated operating speeds for new highway designs. Terrain, area type (urban versus rural), and functional class were all considered. The study findings were as follows:

1. In urban areas, designers generally selected design speeds within the range of anticipated operating speeds, regardless of terrain or functional class. The selected design speed was often equal to or 5 mph higher than the anticipated posted speed limit across terrain types and functional classifications.
2. In rural areas, designers generally selected design speeds within the range of anticipated operating speeds, regardless of terrain or functional class. The selected design speed was nearly always 5 mph higher than the anticipated posted speed limit across terrain types and functional classifications.

Design speed is conceptually intended to be consistent with operating speeds at the higher end of the speed distribution observed on a road segment. In other words, the majority of drivers travel at or below the design speed. Pre-2001 definitions of design speed implied that drivers traveling at or below the design speed were traveling at a safer speed than drivers traveling above the design speed. However, traveling above the design speed is not necessarily less safe than traveling below the design speed. Safety on road segments with different design speed–operating speed relationships has not been thoroughly researched.

Expected relationships between design speed and average running speed, with running speed defined as "the length of the highway section divided by the running time required for the vehicle to travel through the section" (*11*), were described as far back as the 1954 and 1957 AASHO design policies (*12, 13*). The same relationships between design speed and average running speed that were presented in these early documents are still reflected in current policy. Running speeds are expected to be close to design speeds when design speeds are low. That "some sections of low design speed highways are frequently overdriven, with an appreciable number of drivers exceeding the design speed" was also recognized (*12*). The speed selected by most drivers is expected to increase as design speed increases, but at a lower rate:

> Comparing the observed average speeds with calculated design speeds, it is found that on sections of highway having a 30-mph design speed
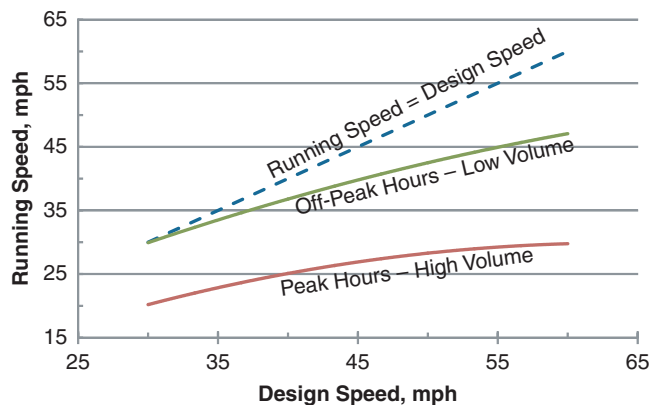

FIGURE 1   Approximate relationships between design and running speeds for urban conditions. [Source: adapted from *A Policy on Arterial Highways in Urban Areas* (*13*).]

> the average running speed is approximately 90% of the design speed. The ratio gradually decreases to about 70% for highway sections with a design speed of 70 mph. (*12*)

In 1957, design speed and running speed relationships were expanded to include numbers for both low volume and peak volumes (*13*). These relationships are illustrated in Figure 1. The numbers for off-peak hours–low-volume conditions are similar to those still in use today for applicable design speeds [see Exhibit 3-14 in *A Policy on Geometric Design of Highways and Streets* (*11*)].

Current practice related to selection of design speed is still influenced by the early definitions of design speed and the ideal design speed–running speed relationships illustrated in Figure 1. The older definitions suggest that a high design speed should be selected if a majority of the drivers will select speeds below the design speed and also if the design speed reflects a maximum safe speed. Operating speeds will likely be close to their targeted range, because they are not expected to increase at a rate directly proportional to design speed. There will also be a larger buffer between operating speeds and design speeds at higher design speed values, which is desirable because, at the time, design speed represented the maximum safe speed. The definition of design speed has changed. Direct references to safety were removed from the current definition, but the same basic philosophy is still reflected in supplemental guidance related to design speed selection: "Except for local streets . . . every effort should be made to use as high a design speed as practical to attain a desired degree of safety" (*11*). Once a design speed is selected, the minimum (or maximum) design values for a number of geometric features are determined.

ESTABLISHING DESIGN CRITERIA

Roadway designers deal with the challenge of designing for a broad range of driver, vehicle, and roadway conditions and capabilities. The challenge is not much different from that of other civil engineering disciplines (e.g., designing a building to withstand a range of future loading conditions that cannot be estimated with certainty). Variability in factors that influence design decisions has traditionally been addressed implicitly in civil engineering disciplines (*14*). Average values are used if the variability in certain parameters influencing design is insignificant. Conservative values are used if
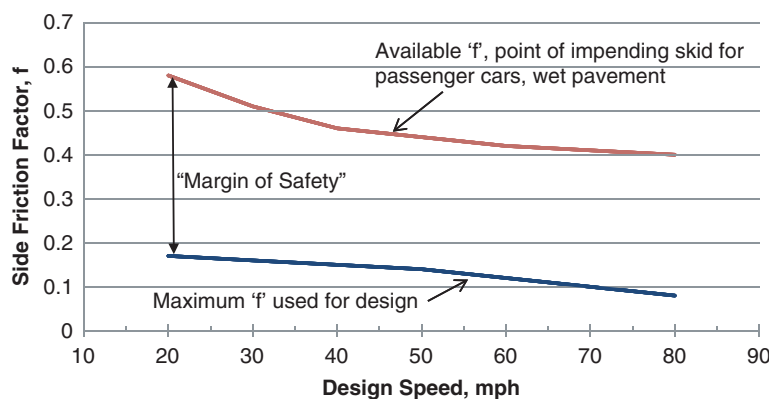
FIGURE 2   Comparison of maximum side friction factor used for design with available side friction.

the variability is large, as is the case with road geometric design. Probabilistic design approaches have been implemented in some engineering disciplines to address variability explicitly (*14*). Some early ideas on potential applications of probabilistic approaches to road design have been offered (*15*), but have not been implemented in U.S. design practice. The remainder of this section reviews the conservative approach taken to establishing road design criteria and uses quantitative examples. The discussion addresses two speed-related design criteria: minimum horizontal curve radius and required stopping sight distance.

The parameters used to establish the minimum horizontal curve radius are the maximum side friction factor and maximum rate of superelevation. Values for the maximum side friction factor are based on driver comfort, not on physical side friction supply-and-demand relationships. The result is a significant margin of safety between friction values used for design and friction supply at the road surface–tire interface at the point of impending skid. The difference is illustrated in Figure 2. The numbers for side friction supply (i.e., available *f* in Figure 2) are based on a recent reanalysis of findings in Harwood et al. (*16*). They are applicable for roadways on level or near-level grades. The effects of the margin of safety illustrated in Figure 2 on determining the minimum design radius of a horizontal curve are illustrated in Figure 3. The line for the minimum curve radius based on truck rollover is added to supplement a discussion later in this paper on large truck considerations.

The parameters used to establish the minimum required stopping sight distance are the perception–reaction time and the deceleration rate. A perception–reaction time of 2.5 s is currently recommended for design (*11*). The 2.5-s perception–reaction time is based on a synthesis of four studies. It is believed to encompass the capabilities of most drivers, including older drivers, and to exceed the 90th percentile of reaction time for all drivers (*11*). A deceleration rate of 11.2 ft/s^2 is used for design (*11*). This value is based on research published in Fambro et al. (*17*). Most drivers decelerate at rates greater than 14.8 ft/s^2, and approximately 90% decelerate at rates greater than 11.2 ft/s^2 (*11*). These rates are well within those that allow drivers to maintain steering control during braking on wet surfaces (*11*).

A conservative road design approach becomes apparent when the limiting parameter values used for the design of horizontal curves and the calculation of required stopping sight distance are compared with the observed parameter values found in published research results. Friction supply is significantly greater than the maximum friction used for design. The perception–reaction time used for design represents a 90th percentile value (i.e., 90% of drivers have faster perception–reaction times). Deceleration rates assumed for design represent a 10th percentile value (i.e., 90% of drivers decelerate at higher rates). The conservative approach is consistent with other civil engineering disciplines. Design values suggest that a majority of drivers can traverse a horizontal curve or stop before hitting an
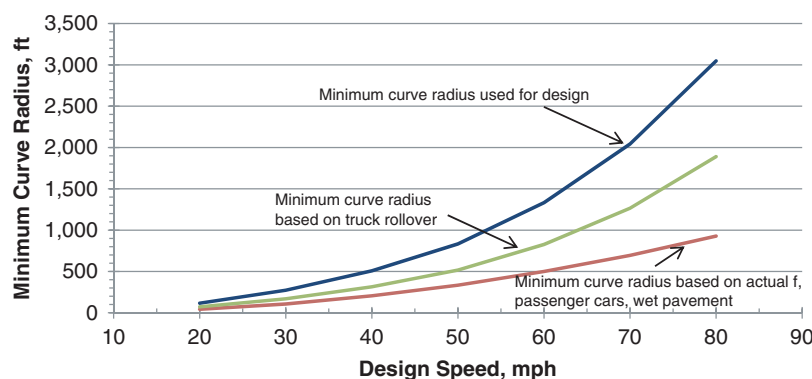
FIGURE 3   Comparison of minimum curve radius used for design with minimum curve radii on the basis of limiting values of side friction for passenger cars on wet pavement and truck rollover thresholds.

object in the roadway if they are traveling faster than the design speed, even if minimum design values are used.

Actual design values are determined once minimum (or maximum) values are established. The Green Book contains a recommendation that "above-minimum design values should be used, where practical" (*11*). Designers are discouraged from using the minimum values for a selected design speed, even though the parameters used to determine the minimum values are conservative. The process results in the inferred design speed, defined as the maximum speed for which all critical design speed–related criteria are met at a particular location, greater than the design speed (*5*). Speed-related road cues perceived by the driver (e.g., available sight distance, horizontal curve sharpness) are more associated with inferred design speed than with design speed. Operating speeds have been shown to increase as inferred design speed increases (*5, 18–19*).

OPERATING SPEED OUTCOMES

The speed-related outcomes of U.S. road design practice are described and illustrated with field data in Donnell et al. (*5*). Figure 4 illustrates a typical outcome on low- to intermediate-speed roads. Design speed is determined during the design process. Inferred design speeds (defined above) are determined implicitly, but typically not considered or calculated, as a result of geometric design decisions. Inferred design speeds are usually higher than the design speed because designers are encouraged to exceed minimum values for geometric design features that are determined on the basis of the design speed. The result is that design features meet criteria for design speeds far greater than the design speed (shown by the inferred design speed line above the designated design speed line in Figure 4). Speed limits are generally posted equal to or less than the design speed (*1*). After a road is open to traffic, actual operating speeds may be higher than both the speed limit and the design speed, as shown in Figure 4. The scenario sometimes leads to a posted speed limit higher than the design speed if the posted speeds are increased to reflect the 85th percentile speed (*5*).

Field observations show that the 85th percentile operating speed tends to be lower than design speeds for design speeds above 55 mph (see Figure 5). The exact crossing point may vary according to area (e.g., urban versus rural) and facility type; data from Himes et al.
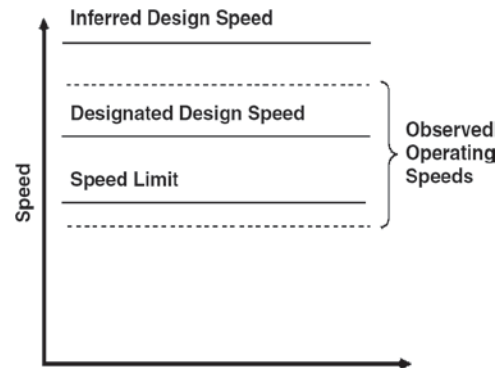
FIGURE 4 Observed speed-related outcomes of typical U.S. design practice. [Source: Donnell et al. (*5*)].

include multiple area and facility types (*20*). Situations with a design speed equal to or higher than operating speeds are as intended and are consistent with the ideal design speed–operating speed relationships that have been described since the early design policies and with other civil engineering design philosophies. Observed 85th percentile speeds tend to be higher than design speeds for design speeds of approximately 55 mph or less (see Figure 5). The difference increases as the design speed decreases. Operating speeds higher than design speeds may be considered undesirable, although no related safety problems have been quantified. A range of stakeholders may provide input to the selection of design speed and the overall physical appearance of a road. The selected design speed is considered representative of the anticipated and desired operating speeds. Discontent, safety, and security concerns may result when operating speeds ultimately turn out to be higher than design speeds, as in Figure 4, particularly if the road was intended to accommodate nonmotorized users or if it runs through developed land uses. A series of retrofit measures for such a location may be explored and implemented at additional cost.

Proactive speed management through the use of roadway geometry (e.g., increased curvature, narrower road allocations for motorized vehicle use) is one possible solution for avoiding higher-than-intended operating speeds. The term "self-enforcing, self-explaining roadway
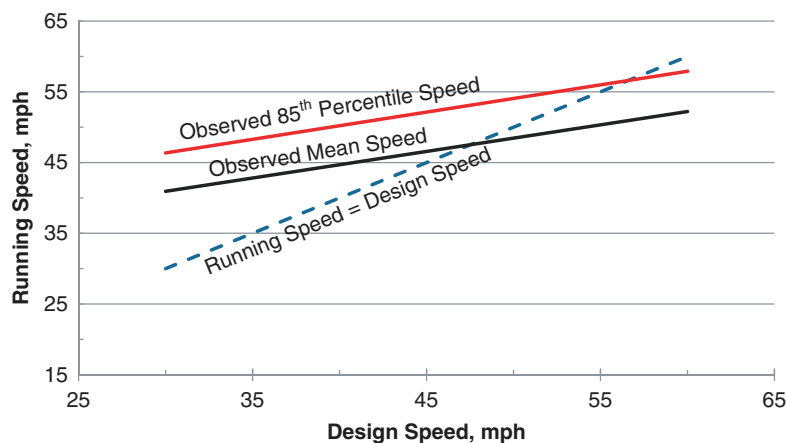
FIGURE 5 Observed relationships between design speed and operating speeds. [Observed 85th percentile speed and observed mean speed estimated with data from Himes et al. (*20*).]

design" has more recently been attached to this concept. This idea is explored in the remainder of the paper.

SPEED MANAGEMENT THROUGH ROAD GEOMETRICS

There are two documented schools of thought related to geometric design, speed, and safety (*21*). The first is consistent with current geometric design policies and practice: in all contexts, a conservative approach to establishing design criteria and wider, more forgiving road dimensions will result in roads that are safer than those with more restrictive geometry. The second is that high-speed design principles have been implemented on intermediate- and lower-speed roads to the safety detriment of all road users. Both views are examined in the remaining sections of this paper. Specific geometric design, speed, and safety issues are examined from a performance-based perspective. The context is whether or not using roadway geometry (e.g., increased curvature, narrower road allocations for motorized vehicle use) is a potentially effective speed management approach that will result in more agreement between target operating speeds and actual operating speeds. The concept is consistent with the idea of self-enforcing, self-explaining roads. The discussion is organized into five questions:

1. What is known about the relationships between road geometry and operating speeds?
2. To what degree does road geometry influence operating speeds?
3. How are safety and security influenced by road geometry?
4. What are the potential impacts on large vehicles?
5. What is the nature of the speed–safety trade-off?

What Is Known About Relationships Between Road Geometry and Operating Speeds?

The TRB research circular *Modeling Operating Speed: Synthesis Report* includes a chapter on knowledge gaps related to relationships between road geometry and operating speeds (*7*). The authors of that chapter concluded that much of what is known about these relationships relates to horizontal curves on rural two-lane highways. Information on the effects of the characteristics of rural two-lane tangents on speed is limited. Knowledge is generally limited to higher-speed roadways; preceding discussion has demonstrated that the need for speed information is greater for moderate- to low-speed roads. Relatively little has been published regarding the speed effects of design decisions on multilane rural roads or roads in suburban and urban areas. These latter area types are likely better suited for speed management through geometrics. The findings of most operating speed studies are applicable to passenger cars only or do not distinguish between passenger cars and trucks.

A majority of operating speed research has looked at measures of speed magnitude. There is limited published research regarding geometric effects on speed variability, as measured by speed variance or standard deviation of speed. Research findings have demonstrated that there are design decisions that are associated with lower measures of speed magnitude but higher measures of speed variance (*22*). In a given scenario, a larger number of drivers may select faster speeds, even though a measure of speed magnitude is lower. Figure 6 demonstrates this point. One design alternative is expected to result in a mean speed that is 5 mph lower than a second design alternative (50 mph versus 55 mph). The standard deviation, however, is expected to be 5 mph higher for the lower mean speed alternative (15 mph versus 10 mph). The 85th percentile speed, therefore, would be the same for both alternatives (65 mph), and the likelihood of someone traveling above 70 mph would actually be higher for the alternative with the lower mean speed. Published knowledge of the interaction of speed magnitude and variability measures with geometric design is only in its early stages [see, for example, Porter and Mason (*22*), Himes and Donnell (*23*), and Porter (*24*)].

To What Degree Does Road Geometry Influence Operating Speeds?

The concept that road geometry can be adjusted to achieve consistency between target speeds and operating speeds is based on
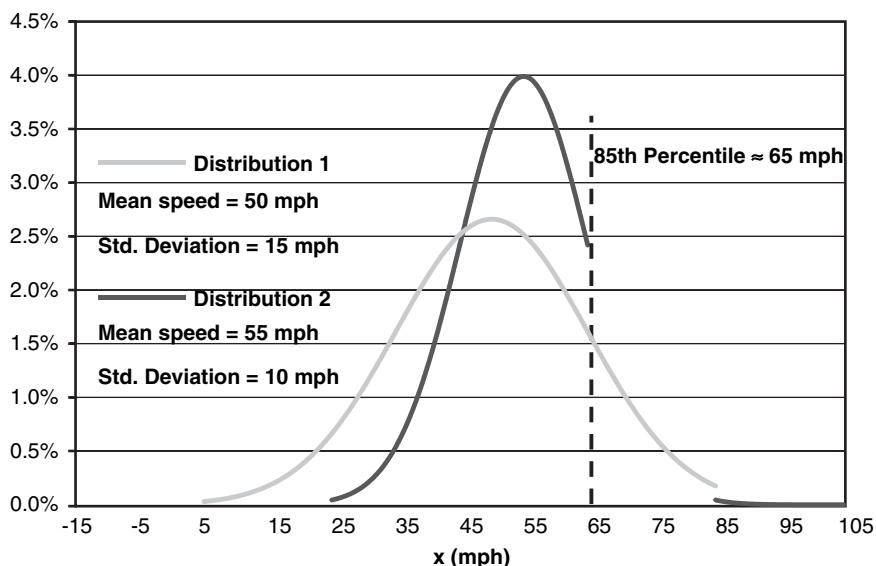

FIGURE 6   Illustration of key speed distribution measures (std. = standard).
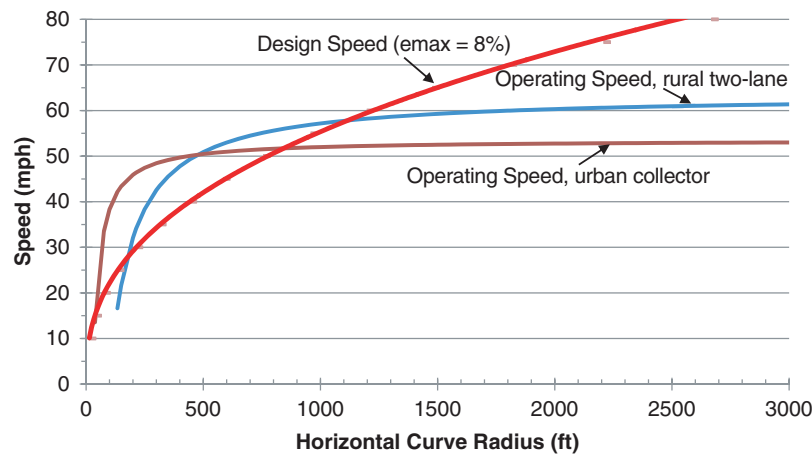
FIGURE 7 Relationships between design speed, horizontal curve radius, and operating speed. [Rural two-lane operating speed line based on Fitzpatrick et al. (*25*); urban collector operating speed line based on Tarris et al. (*26*); emax = maximum rate of superelevation.]

the premise that changes in geometry will affect operating speeds. Research has shown, however, that geometric design decisions may not influence operating speeds unless very constrained dimensions are used. This finding may be counterintuitive, given that geometric design criteria are dependent on design speed. These concepts are illustrated in Figure 7. The relationships show that design speed changes as minimum horizontal curve radius changes for all radii values shown. The slope of the line increases for radii less than approximately 500 ft. Operating speeds, however, do not change significantly as a function of horizontal curve radius until the radius becomes less than approximately 1,000 ft on rural highways and 500 ft on urban collectors. Similar inelastic relationships between operating speeds and road geometry can also be demonstrated for vertical curvature (*25*) and lane width (*27*).

How Are Safety and Security Influenced by Road Geometry?

Adjusting road geometry to achieve harmony between target speeds, design speeds, and operating speeds or implementing ideas similar to self-enforcing, self-explaining road design might also impact safety and security. Hauer explains the differences between safety and security, defining safety as "the number of accidents (crashes), or accident consequences, by kind and severity, expected to occur on the entity during a specified period" and security as "people's subjective perception of safety" (*28*). The effects that changing road geometry to dampen speeds will have on safety, security, or both and how the effects will differ across road user types have not been documented. Possible outcomes are illustrated in Figure 8.

The concept of self-enforcing, self-explaining road design is based on a desired change in performance from D to D′ for drivers of motorized vehicles: drivers will feel less secure and select lower speeds; their safety will improve as a result. For nonmotorized users of the road, the concept is based on a desired change from E to E′: nonmotorized users feel more secure and are also safer when motorized vehicle speeds are lower. It is unclear how trade-offs will be assessed if other scenarios result. For example, narrower cross-section allocations for vehicle use may result in a move from A to A′ for nonmotorized users (an increase in security with no change in

safety) and a change from F to F′ for motorized vehicles (a decrease in both security and safety). The number of potential outcomes is large, as reflected by possible combinations of the outcomes shown in Figure 8.

What Are Potential Impacts on Large Vehicles?

The preceding discussion demonstrated that operating speeds may not be influenced by geometric design decisions unless very constrained dimensions are used. The effects of these tighter, smaller dimensions on larger vehicles need to be fully understood if geometry is to be used as a speed management strategy. Effects resulting from decreased separation between opposing vehicles, offtracking, and increased rollover potential will need to be adequately examined. Figure 3 demonstrates the relationship between horizontal curve radius and truck rollover thresholds. Minimum radii based on truck rollover thresholds are larger than those based on impending slide for passenger cars. Therefore, a change in the philosophy of horizontal curve design needs to consider effects on large vehicles. Effects on trucks associated with changes in other geometric elements
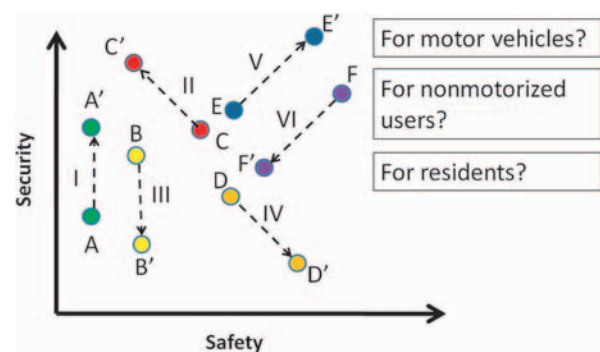

FIGURE 8 Possible safety and security outcomes of using roadway geometry as a speed management tool. [Concept adapted from Hauer (*28*).]
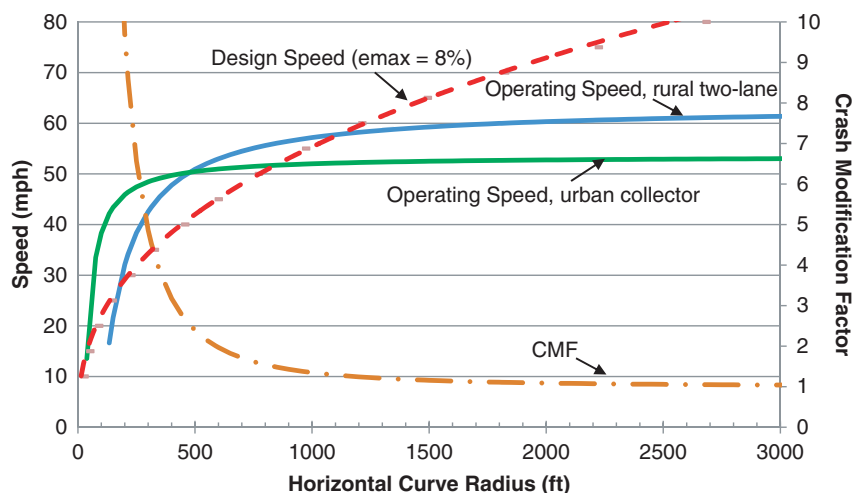
FIGURE 9 Relationships between horizontal curve radius and speed and horizontal curve radius and safety. [Rural two-lane operating speed line based on Fitzpatrick et al. (*25*); urban collector operating speed line based on Tarris et al. (*26*); CMF line based on HSM (*6*).]

(e.g., lane width, shoulder width, grade, vertical curvature) also need to be explored and quantified in this manner.

What Is the Nature of
Speed–Safety Trade-Off?

The Complete Streets Toolkit of the Sacramento Area Council of Governments raises a question related to self-explaining roads: "Are we ready to trade speed for safety?" (*29*). Tools to quantify safety are becoming increasingly available and have the potential to uncover certain combinations of design elements that lead to safer conditions than those that are determined by applying design policy or standards alone. The most widely recognized safety prediction tool is the HSM. Information in the HSM currently supports geometric design policy:

more forgiving geometric designs generally tend to offer improved safety performance (i.e., fewer expected crashes). The horizontal curvature crash modification factor (CMF) in the HSM for rural two-lane highways is overlaid onto the design speed and operating speed relationships in Figure 9 to illustrate this point. The horizontal curve radius influences vehicle operating speeds; however, the effect is nominal until the radius falls below approximately 1,000 ft. Similarly, the expected crash frequency changes only nominally until the horizontal curve radius falls below 1,000 ft. The graph shows that if speed reduction is attempted by designing horizontal curves with tighter radii, an increase in crashes should also be expected. Figure 10 shows similar trade-offs for lane width.

The effect that the HSM in its current form will have on design philosophy, design decisions, and the resulting operating speed conditions is unclear. Quantitative safety information in the manual is
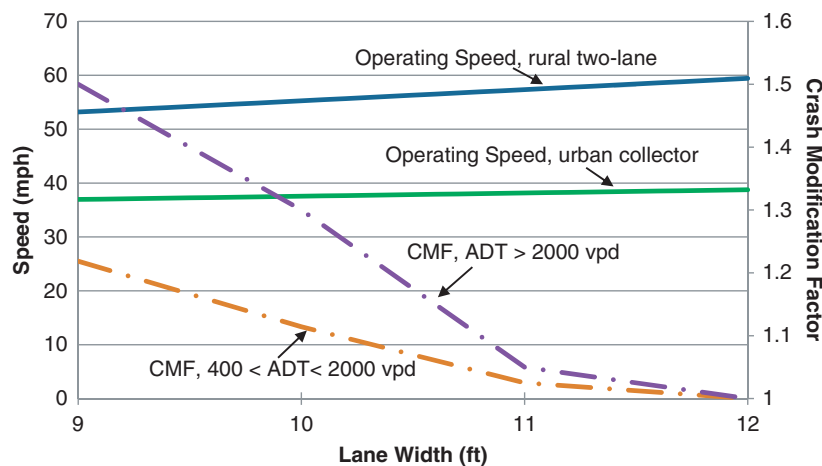

FIGURE 10 Relationships between lane width and speed and lane width and safety. [Rural two-lane operating speed line based on Lamm and Choueiri (*30*); urban collector operating speed line based on Tarris et al. (*26*); CMF line based on HSM (*6*). ADT = average daily traffic; vpd = vehicles per day.]

currently consistent with qualitative safety statements that have been part of design policy for many years. Some published safety studies indicate that there are cases where narrower cross sections are not necessarily less safe. For example, Gross et al. developed CMFs for lane and shoulder width combinations on rural two-lane highways (*31*). The interactions between lane width and shoulder width were accounted for during CMF estimation by using a case–control methodology. The results were much different from the CMFs in the HSM and yielded the following logical conclusions:

• Shoulder width has a larger effect on safety when lanes are narrow, but the effect of shoulder width decreases as lane width increases.
• An increase in lane width does not always result in an increase in safety, particularly when shoulder widths are wider.

Rural two-lane highway segments with lane and shoulder width combinations totaling 16 to 17 ft (e.g., 10-ft lanes with 6-ft shoulders; 11-ft lanes with 6-ft shoulders; and 12-ft lanes with 5-ft shoulders) may not be any less safe than rural two-lane highway segments that meet HSM base conditions (i.e., 12-ft lanes with 6-ft shoulders). Bonneson and Pratt also estimated interactions between lane and shoulder width, and their results have similar implications: the safety effect of lane width depends on the shoulder width (*32*).

Research on the relationship between lane width and safety on urban and suburban arterials that was conducted as part of the development of the HSM concluded, "No consistent relationship was found between lane width and safety. Therefore, lane width was not included in the model" (*33*). Other research on lane width in urban areas indicated that the variable

broad lane indicator (lanes wider than 3.69 meters) was associated with a higher frequency of *Urban* section run-off-roadway accidents. A plausible explanation is that a broader lane could be expected to allow a higher traveling speed, creating a greater likelihood for run-off-roadways [crashes] on *Urban* sections. (*34*)

SUMMARY AND CONCLUSIONS

This paper explored the interaction of geometric design, speed, and safety. A performance-based approach to this topic was considered more possible given the availability of two key documents: the *Highway Safety Manual* (*6*) and *Modeling Operating Speed: Synthesis Report* (*7*). A historical look at design speed concepts showed that although the definition of design speed has changed on more than one occasion, the same basic philosophy that relates design speed to a safe speed is still reflected in current policy in supplemental guidance related to the selection of design speed. A conservative approach to establishing design criteria, used to address the range of driver, vehicle, and roadway conditions and capabilities that a designer must consider, was demonstrated. Operating speeds were shown to be higher than design speeds for design speeds of approximately 55 mph or less. This outcome may be considered undesirable, but that categorization seems to be based more on subjective judgments of what is desirable than on actual safety findings. Safety on road segments with different design speed–operating speed relationships has not been thoroughly researched, and it is unclear whether alternatives to current design speed selection practices would result in improved safety performance. Finally, the idea of speed management through the use of roadway geometrics (i.e., geometric designs

that influence driver selection of operating speed)—one component of self-enforcing, self-explaining roadway design—was explored. Findings uncovered possible challenges to implementing this idea.

Published knowledge on relationships between road geometry and operating speeds is limited to specific conditions. Much of what is currently known is for passenger cars traveling on horizontal curves on rural two-lane highways. There are knowledge gaps related to other design features, vehicle types, and facility types. The interaction of speed magnitude and variability measures with geometric design, demonstrated in the paper to be an important interaction to understand, has only been documented for a limited number of scenarios. Research has also shown that operating speeds may not be sensitive to geometric design decisions unless very constrained dimensions are used.

The effects that adjusting road geometry to achieve harmony between target speeds, design speeds, and operating speeds will have on safety, security, or both are also unknown. The distinctions are important and need to be quantified to fully assess the range of such outcomes that may occur for different road users and other stakeholders. The effects of tighter, narrower, or smaller road dimensions on the operation and safety of larger vehicles need to be adequately examined.

Finally, the two key documents referenced at the beginning of this paper seem to indicate that geometric design decisions made to reduce speeds (e.g., increased curvature, narrower road allocations for motorized vehicle use) are expected to increase crashes. The speed and safety assessment of geometric design features showed that, according to the HSM, more forgiving geometric designs generally tend to offer improved safety performance (i.e., fewer expected crashes); however, these geometrics tend also to produce higher vehicle operating speeds. Some published safety studies indicate that narrower cross sections are not necessarily less safe than wider cross sections; effects may depend on an interaction between lane width and shoulder width. Current evidence on whether reduced safety is always a trade-off associated with geometric design decisions made to reduce speeds is conflicting.

RECOMMENDATIONS

A strategic and cooperative approach from the practitioner, government, and research communities is needed to answer the questions raised in this paper regarding relationships between geometric design, speed, and safety. A few possible ideas for moving forward are summarized in this section:

• Research reviewed in preparing this paper revealed that speed-related and safety-related studies are conducted independently. Future research efforts should be designed to consider both performance measures simultaneously. Interactions between geometric design, speed, and safety are complex. Considering these interactions within a single study is more likely to uncover relationships that are more reflective of reality than is combining the results of individual efforts, as was done in Figures 9 and 10.
• Most research on speed- and safety-related geometric design has looked at the effects of design elements in isolation and then combined the isolated effects through some additive or multiplicative process. These isolated effects may not be sufficiently accurate when atypical combinations of design elements are present. Considering criteria combinations (i.e., interactions) is more likely to uncover unique designs that will influence safety and speed in the

desired directions than is considering only individual features. The performance effects of criteria combinations should be central to future work on the operational and safety impacts of geometrics. An example that uses lane and shoulder width is provided in this paper.

• Most models for predicting speed and safety are estimated by relating crashes and speed at some location to traffic, roadway, and other surrounding features at that same location. The concept of driver expectancy recognizes that drivers will make decisions based on previous experience. Speed and safety models should also consider previous driver experience (e.g., what conditions did drivers encounter upstream of the modeled location?) in predicting speed selection and crash occurrence.

REFERENCES

1. Fitzpatrick, K., P. Carlson, M. A. Brewer, M. D. Wooldridge, and S.-P. Miaou. *NCHRP Report 504: Design Speed, Operating Speed, and Posted Speed Practices.* Transportation Research Board of the National Academies, Washington, D.C., 2003.
2. Donnell, E. T., S. C. Himes, K. M. Mahoney, R. J. Porter, and H. McGee. *Speed Concepts: Informational Guide.* Publication FHWA-SA-10-001. FHWA, U.S. Department of Transportation, 2009.
3. *Traffic Safety Facts 2009* (Early Edition). Publication DOT HS 811 402. NHTSA, U.S. Department of Transportation, 2009.
4. Dumbaugh, E., and W. Li. Designing for the Safety of Pedestrians, Cyclists, and Motorists in Urban Environments. *Journal of the American Planning Association,* Vol. 77, No. 1, 2011, pp. 69–88.
5. Donnell, E. T., S. C. Himes, K. M. Mahoney, and R. J. Porter. Understanding Speed Concepts: Key Definitions and Case Study Examples. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2120,* Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 3–11.
6. *Highway Safety Manual,* 1st ed. AASHTO, Washington, D.C., 2010.
7. *Transportation Research Circular E-151: Modeling Operating Speed: Synthesis Report.* Transportation Research Board of the National Academies, Washington, D.C., 2011.
8. Tarris, J. P., J. M. Mason, Jr., and N. D. Antonucci. Geometric Design of Low-Speed Urban Streets. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1701,* TRB, National Research Council, Washington, D.C., 2000, pp. 95–103.
9. *A Policy on Highway Types (Geometric).* AASHO, Washington, D.C., 1940.
10. *A Policy on Geometric Design of Highways and Streets.* AASHTO, Washington, D.C., 1984.
11. *A Policy on Geometric Design of Highways and Streets.* AASHTO, Washington, D.C., 2004.
12. *A Policy on Geometric Design of Rural Highways.* AASHO, Washington, D.C., 1954.
13. *A Policy on Arterial Highways in Urban Areas.* AASHO, Washington, D.C., 1957.
14. Benjamin, J. R., and C. A. Cornell. *Probability, Statistics, and Decision for Civil Engineers.* McGraw-Hill, Inc., New York, 1970.
15. Ismail, K., and T. Sayed. Risk-Based Highway Design: Case Studies from British Columbia, Canada. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2195,* Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 3–13.
16. Harwood, D. W., D. J. Torbic, K. R. Richard, W. D. Glauz, and L. Elefteriadou. *NCHRP Report 505: Review of Truck Characteristics as Factors in Roadway Design.* Transportation Research Board of the National Academies, Washington, D.C., 2003.
17. Fambro, D. B., K. Fitzpatrick, and R. J. Koppa. *NCHRP Report 400: Determination of Stopping Sight Distances.* TRB, National Research Council, Washington, D.C., 1997.
18. Krammes, R. A., R. Q. Brackett, M. A. Shafer, J. L. Ottesen, I. B. Anderson, K. L. Fink, K. M. Collins, O. J. Pendleton, and C. J. Messer. *Horizontal Alignment Design Consistency for Rural Two-Lane Highways.* Publication FHWA-RD-94-034. FHWA, U.S. Department of Transportation, 1994.
19. Fitzpatrick, K., C. B. Shamburger, R. A. Krammes, and D. B. Fambro. Operating Speed on Suburban Arterial Curves. In *Transportation Research Record 1579,* TRB, National Research Council, Washington, D.C., 1997, pp. 89–96.
20. Himes, S. C., E. T. Donnell, and R. J. Porter. New Insights on Evaluations of Design Consistency for Two-Lane Highways. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2262,* Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 31–41.
21. Ewing, R., and E. Dumbaugh. The Built Environment and Traffic Safety: A Review of Empirical Evidence. *Journal of Planning Literature,* Vol. 23, No. 4, 2009, pp. 347–367.
22. Porter, R. J., and J. M. Mason. Modeling Speed Behavior of Passenger Cars and Trucks in Freeway Construction Work Zones: Implications on Work Zone Design and Traffic Control Decision Processes. *Journal of Transportation Engineering,* Vol. 134, No. 11, 2008, pp. 450–458.
23. Himes, S. C., and E. T. Donnell. Speed Prediction Models for Multilane Highways: Simultaneous Equations Approach. *Journal of Transportation Engineering,* Vol. 136, No. 10, 2010, pp. 855–862.
24. Porter, R. J. Exploring the Relationship Between Macroscopic Speed Parameters, Road Geometrics, and Traffic Control: An Empirical Study During Low-Volume Conditions in Construction Work Zones. Presented at 90th Annual Meeting of the Transportation Research Board, Washington, D.C., 2011.
25. Fitzpatrick, K., L. Elefteriadou, D. W. Harwood, J. M. Collins, J. McFadden, I. B. Anderson, R. A. Krammes, N. Irizarry, K. D. Parma, K. M. Bauer, and K. Passetti. *Speed Prediction for Two-Lane Rural Highways.* Publication FHWA-RD-99-171. FHWA, U.S. Department of Transportation, 2000.
26. Tarris, J. P., C. M. Poe, J. M. Mason, Jr., and K. G. Goulias. Predicting Operating Speeds on Low-Speed Urban Streets: Regression and Panel Analysis Approaches. In *Transportation Research Record 1523,* TRB, National Research Council, Washington, D.C., 1996, pp. 46–54.
27. Poe, C. M., and J. M. Mason, Jr. Analyzing Influence of Geometric Design on Operating Speeds Along Low-Speed Urban Streets: Mixed-Model Approach. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1737,* TRB, National Research Council, Washington, D.C., 2000, pp. 18–25.
28. Hauer, E. *Observational Before-After Studies in Road Safety.* Pergamon, New York, 1997.
29. Sacramento Area Council of Governments. *Complete Streets Resource Toolkit.* http://www.sacog.org/complete-streets/toolkit/files/bibliography.html. Accessed August 1, 2011.
30. Lamm, R., and E. M. Choueiri. Recommendations for Evaluating Horizontal Design Consistency Based on Investigations in the State of New York. In *Transportation Research Record 1122,* TRB, National Research Council, Washington, D.C., 1987, pp. 68–78.
31. Gross, F., P. P. Jovanis, and K. A. Eccles. Safety Effectiveness of Lane and Shoulder Width Combinations on Rural, Two-Lane, Undivided Roads. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2103,* Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 42–49.
32. Bonneson, J. A., and M. P. Pratt. *Roadway Safety Design Workbook.* Publication FHWA/TX-09/0-4703-P2. Texas Transportation Institute, Texas A&M University System, College Station, 2009.
33. Harwood, D. W., K. M. Bauer, K. R. Richard, D. K. Gilmore, J. L. Graham, I. B. Potts, D. J. Torbic, and E. Hauer. *NCHRP Web-Only Document 129: Phases I and II. Methodology to Predict the Safety Performance of Urban and Suburban Arterials.* Transportation Research Board of the National Academies, Washington, D.C., 2007.
34. Lee, J., and F. Mannering. *Analysis of Roadside Accident Frequency and Severity and Roadside Safety Management.* Final Research Report: Project T9903, Task 97. Washington State Department of Transportation, Olympia, 1999.